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Title: Conventional and novel body temperature measurement during rest and exercise induced hyperthermia

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Abstract

Despite technological advances in thermal sensory equipment, few core temperature (T_{CORE}) measurement techniques have met the established validity criteria in exercise science. Additionally, there is debate as to what method serves as the most practically viable, yet upholds the proposed measurement accuracy. This study assessed the accuracy of current and novel T_{CORE} measurement techniques in comparison to rectal temperature (T_{REC}) as a reference standard. Fifteen well-trained subjects (11 male, 4 female) completed 60 min of exercise at an intensity equating to the lactate threshold; measured via a discontinuous exercise test. T_{REC} was significantly elevated from resting values ($37.2 \pm 0.3^{\circ}\text{C}$) at the end of moderate intensity exercise ($39.6 \pm 0.04^{\circ}\text{C}$; $P = 0.001$). Intestinal telemetric pill (T_{PILL}) temperature and temporal artery temperature (T_{TEM}) did not differ significantly from T_{REC} at rest or during exercise ($P > 0.05$). However, aural canal temperature (T_{AUR}) and thermal imaging temperature (T_{IMA}) were both significantly lower than T_{REC} ($P < 0.05$). Bland Altman analysis revealed only T_{PILL} was within acceptable limits of agreement (mean bias; 0.04°C), while T_{TEM} , T_{AUR} and T_{IMA} demonstrated mean bias values outside of the acceptable range ($> 0.27^{\circ}\text{C}$). Against T_{REC} , these results support the use of T_{PILL} over all other techniques as a valid measure of T_{CORE} at rest and during exercise induced hyperthermia. Novel findings illustrate that T_{IMA} (when measured at the inner eye canthus) shows poor agreement to T_{REC} during rest and exercise, which is similar to other 'surface' measures.

Key words: Core temperature, moderate exercise, hyperthermia.

1. Introduction

Hyperthermia affects exercise performance and increases the risk of the athlete experiencing heat exhaustion and heat stroke (Moran & Mendal, 2002; Taylor *et al.*, 2014). There have been numerous sites identified to estimate core temperature (T_{CORE}) for the purpose of monitoring thermoregulatory response to exercise. These include; pulmonary artery (catheter), rectal, oesophageal, intestinal, temporal artery, oral, aural canal, tympanum and axilla (Huggins *et al.*, 2012; Lim *et al.*, 2008).

Core temperature is most correctly defined as the temperature of the hypothalamic blood flow (Robinson *et al.*, 1998), however, this cannot be directly measured due to its anatomical location. The pulmonary artery is the most accurate site to measure T_{CORE} due to its interaction with central blood flow (Lim *et al.*, 2008; Moran & Mendal, 2002), however, unfortunately the procedure is extremely invasive and not suitable in the exercise setting. Rectal temperature (T_{REC}) has been criticised for its slow response to fluctuations in central blood temperature (Gagnon *et al.*, 2010), while oesophageal, stomach and tympanic membrane temperatures show faster response times (Molnar & Read, 1974; Kolka *et al.*, 1993; Shiraki *et al.*, 1986). Despite T_{REC} not accurately reflecting brain temperature (Childs *et al.*, 2005; Taylor *et al.*, 2014), it is deemed a valid and practical reference standard within the exercise science setting due to its stability in steady state conditions (Gagnon *et al.*, 2010; Ganio *et al.*, 2009; Sawka & Wenger, 1988). In addition, monitoring T_{REC} in athletes under exercise induced heat stress is recommended by the National Athletic Trainers' Association (NATA) to help prevent heat illness (Casa *et al.*, 2015).

Multiple studies have validated the telemetric intestinal pill against both oesophageal temperature (Lee *et al.*, 2000; O'Brien *et al.*, 1998) and T_{REC} measurement methods (Darwent *et al.*, 2011; Gant *et al.*, 2006; McKensie & Osgood, 2004). However, it has recently been demonstrated that intestinal temperature (T_{INT}) does not mirror T_{REC} when cold fluid was ingested during a half marathon (Savoie *et al.*, 2015). Other authors also found that fluid intake during exercise can result in transient reductions in telemetric pill temperature (T_{PILL}), even up to 8 hours after sensor ingestion (Engels *et al.*, 2009; Wilkinson *et al.*, 2008).

Direct measurement of the tympanic membrane is also suggested to be a valid site to measure of T_{CORE} (Benzinger & Benzinger, 1972), potentially due to its good perfusion from the carotid artery (Jay *et al.*, 2007; Lim *et al.*, 2008). Aural canal temperature (T_{AUR}) shows poor validity compared to T_{REC} when measured using a commercial hand held device during exercise (Armstrong *et al.*, 1994; Deschamps *et al.*, 1992). Nonetheless, the model of device and method employed may contribute to the discrepancies reported (Easton *et al.*, 2007). Similar to T_{AUR} , the temporal scanner utilises infra-red radiation from the skin above the temporal artery (mainly superficial; dependant on technique used) to attain a T_{CORE} reading (Kistemaker *et al.*, 2006). Thereafter, an algorithm which considers skin to core temperature gradients and ambient temperature calculates T_{CORE} (Low *et al.*, 2007). Poor agreement has been documented between temporal artery temperature (T_{TEM}) and reference standards (Casa *et al.*, 2007; Kistemaker *et al.* 2006), including T_{REC} . However, it is still unclear whether this is due to variation in scanning patterns utilised, environmental settings (clinical vs exercise), or interference from profuse sweating (Ganio *et al.*, 2009; Low *et al.* 2007).

Thermal imaging temperature (T_{IMA}) measurement techniques have also been considered as surrogate measures of T_{CORE} , using the facial vasculature to assess convectional heat distribution from capillary blood flow (Bourlai *et al.*, 2012). Thermal cameras are used to examine fever in clinical patients via facial imaging (particularly the inner canthus of the eye), with reported temperatures in excess of 38.0°C (Ring & Ammer, 2012). Thermal imaging has been deemed a valid measure of skin temperature in thermoneutral and hot environments (Costello *et al.*, 2013). Conversely, James *et al.* (2014) found poor validity (Mean bias; -1.4°C) when T_{IMA} was used to measure skin temperature during exercise compared to a hard wired thermistor system. Nonetheless, improved validity may be observed when examining peak temperature readings from the face and forehead, where considerable heat evaporation occurs (Easton *et al.*, 2007). Teunissen and Daanen (2011) compared the agreement between T_{IMA} (inner eye canthus) and oesophageal temperature during active and passive heating, finding poor agreement between the two. However, to our knowledge there is no published data examining the validity of T_{IMA} against T_{REC} as a reference standard, during moderate intensity exercise in thermally challenging conditions.

A lack of acceptability among the various T_{CORE} measurement methods still exists. Despite certain T_{CORE} measurement techniques possessing adequate validity during rest and exercise (T_{REC} and T_{PILL}), there are practical issues with these methods. This study aims to examine novel and conventional temperature measurement devices and techniques to attain valid T_{CORE} readings (using T_{REC} as the reference standard) during rest and exercise induced hyperthermia.

2. Methods

2.1 Participants & study design

Following attainment of ethics approval from the St. Mary's University ethics committee, volunteer study participants were recruited. Fifteen well-trained athletes participated in this study; see table 1. All participants provided written informed consent, along with a detailed medical history questionnaire. Participants were instructed on protocols used and on the potential risks and discomfort with each.

INSERT TABLE 1. HERE.

This study involved two visits to the laboratory. In visit 1, anthropometric characteristics were measured before the subject completed a 10 min warm-up at room temperature (19 – 21°C). After the warm-up a discontinuous incremental exercise test was carried out to identify lactate threshold (LT) and lactate turnpoint (LTP), followed by an incremental test to exhaustion to record maximal aerobic capacity ($\dot{V}O_{2\text{MAX}}$). Full details are provided below. On visit 2, subjects carried out exercise in a heated environmental chamber (Sporting Edge, UK). The subject was fitted with thermal sensory equipment before exercising at the intensity equating to LT for 60 min. No fans were used to direct airflow onto the participants. This minimised convective air cooling, therefore, allowing more standardised comparisons between 'surface' and 'deeper' T_{CORE} measures in a thermally challenging environment.

2.2 Visit 1 - Preliminary testing

Stature and nude body mass were attained before skinfold thickness (mm) was measured by the same researcher using a 4 site skinfold measurement technique (bicep, tricep, subscapular and supra-iliac) (Durnin & Wormersley, 1974). Following the warm-up the subject was fitted with a mask for breath-by-breath expired air analysis (Jaeger Oxycon Pro, Hoechberg, Germany). Heart rate (HR) was recorded throughout exercise (Polar Team System®, Polar UK).

Exercise was completed on either a motorised treadmill (Woodway ELG, Woodway USA, Forester Court, WI, 53209) or a cycling ergometer (SRM, Julich, Germany) depending on the athletes preferred mode of exercise. The discontinuous running test incorporated 3 min work efforts followed by a 30s static recovery period whereby the subject straddled the treadmill belt. Each progressive intensity was 1 km·hr⁻¹ faster than the previous. During recovery periods, a blood sample was attained via capillary puncture for blood lactate (BLa) analysis (Biosen C-Line, EKF Diagnostics, Germany) and ratings of perceived exertion (RPE) were gathered on a 15 point scale (Borg, 1970). The discontinuous cycling test incorporated 4 min work efforts, while each progressive intensity was 25W higher than the previous power output (PO). Physiological and perceptual measurements (BLa & RPE) were collected during the final 30s of each stage. Each subject performed 5 – 9 submaximal stages starting at an intensity below LT [start speed or PO was estimated using previous race-times]. Velocity or PO at LT (vLT / PO@LT) was identified as the first clear inflection point above resting levels along the BLa vs. velocity or PO curve (Svedahl & MacIntosh, 2003). Both submaximal oxygen consumption ($\dot{V}O_2$) and HR were averaged over the final minute of each submaximal exercise stage.

The maximal exercise test began at a PO or run speed equating to the LTP; the second clear inflection point on the BLa vs. velocity or PO curve near the 4 mmol·L⁻¹ lactate concentration (Davis, 1983). Treadmill velocity remained constant during the test, while the treadmill gradient (beginning at 1%) increased by 1% every min until volitional exhaustion. The maximal cycling ramp test intensity increased from the starting PO by 5 W every 15 s until volitional exhaustion. $\dot{V}O_{2MAX}$ was calculated

by measuring the highest 30 s average $\dot{V}O_2$. Maximum HR (HR_{MAX}) was automatically calculated using Polar Pro Trainer 5® software.

2.3 Visit 2 – Moderate intensity exercise

The subject was weighed, before being instructed to go to the lavatory to insert a rectal thermometer 10cm beyond the anal sphincter. On return, T_{PILL} readings were tested and the researcher confirmed whether or not these were in normal physiological range (35.6 – 38.0 °C; Taylor *et al.*, 2014). Measurements of T_{CORE} (T_{REC} , T_{PILL} , T_{AUR} , T_{TEM} and T_{IMA}) and thermal sensation (T_s) were then taken (Table 2) following an initial period in a thermoneutral environment ($23.2 \pm 1.5^\circ\text{C}$, $49 \pm 6\%$ relative humidity) and again after the subject rested in a supine position inside the heated environmental chamber ($29.8 \pm 0.9^\circ\text{C}$, $50 \pm 4\%$ relative humidity) for a 15 min period.

INSERT FIG. 1. HERE.

The subject then began 60 min of exercise at vLT or PO@LT for running and cycling respectively, with perceptual (RPE, T_s), physiological (HR, BL_a) and T_{CORE} measurements recorded at 10 min intervals (Fig 1). On completion, the subject rested in a supine position for 15 min while T_{CORE} and perceptual measurements were noted. When the subject had removed the rectal thermometer, the trial concluded by measuring post-exercise body mass in order to estimate sweat loss. Each subject was allowed to consume water *ad libitum* during the trial and this volume was taken into account in sweat loss calculations.

INSERT TABLE 2. HERE.

2.4 Statistical Analysis

Data are described with mean \pm S.D. values following tests of normality using visual inspection of histogram plots and Shapiro Wilks test scores. The five different temperature devices (T_{REC} , T_{PILL} , T_{AUR} , T_{TEM} and T_{IMA}) were computed using a repeated measures analysis of variance (ANOVA). A statistically significant F-value was observed when $P < 0.05$ and significant differences were followed up using Scheffe post hoc analysis.

Pearson's correlation coefficients (r) were used to evaluate the strength of the relationship between each temperature device and the reference standard, along with the coefficient of multiple determination (R_2) values to examine variability around the mean. Following visual inspection of individual scatterplots, if a time lag was suspected between a measurement device and the reference standard and both were not significantly different ($P > 0.05$), a cross-correlation analysis was carried out. This allowed generation of a cross correlation function (CCF) value for analysis at each time point along the x-axis.

Scedasticity was examined using methods employed by Bagley *et al.* (2011) who used the coefficient of determination (R_2) and a horizontal plot to visually analyse the mean values and absolute differences. Agreement between each temperature device and the criterion measure was analysed using the Bland and Altman (1986) method. Mean bias was calculated by attaining the S.D. of the mean difference between each temperature device and the criterion, while limits of agreement were set when the attained value was multiplied by 1.96. In line with other authors (Casa *et al.*, 2007; Ganio *et al.*, 2009), when a mean bias of greater than 0.27°C was detected the device was reported as invalid.

Statistical analysis was performed on SPSS (version 10 for Windows; SPSS Inc, Chicago, IL) and statistical significance was set at $P < 0.05$. Bland Altman and cross correlation analysis were carried out using R software TM for statistical computing (R Development Core Team).

3. Results

Throughout visit 2, a total of 634 temperature data points were collected between 6 measurement methods. Of the 131 total temperature measurement intervals, 96 measurements were collected for T_{REC} , with 35 of 131 data points not recorded due to reading failures during running trials. A total of 111 measurements were recorded for T_{PILL} ; on two occasions T_{PILL} displayed temperature readings far outside of normal resting range on the telemetric receiver, in which case the data were discarded. In addition, one subjects' T_{PILL} readings began to drop towards resting levels ($\approx 37.0^{\circ}\text{C}$) despite

completing more than 30 min exercise in thermally stressful conditions, with the subject showing a clear rise in all other T_{CORE} measures. This was likely to be as a result of fluid cooling the device in the upper gastrointestinal tract, and in this case four data points were also discarded. T_{AUR} , T_{TEM} and T_{S} were recorded at every measurement interval, while T_{IMA} was recorded during 4 exercise trials with 31 data points logged.

During moderate intensity exercise, as expected, T_{REC} , T_{PILL} , T_{AUR} , T_{TEM} and T_{IMA} were significantly elevated above resting values ($F_{(2,3,83)} = 105.31$, $P < 0.001$, Fig. 2). A significant interaction between time and temperature device was observed ($F_{(9,2,83)} = 3.709$, $P < 0.001$).

Both T_{PILL} and T_{TEM} were not different to T_{REC} during exercise ($P = 1.0$ and $P = 0.079$, respectively; Fig. 2a). Significant correlations were also observed between T_{REC} and T_{PILL} ($r = 0.935$, $P < 0.001$), along with T_{REC} and T_{TEM} ($r = 0.734$, $P < 0.001$). Both T_{AUR} and T_{IMA} were significantly lower than T_{REC} ($P = 0.012$ and $P = 0.003$ respectively), with differences observed at every time point except for post 15 min rest in the environmental chamber (Fig. 2b). A strong correlation for T_{AUR} ($r = 0.834$, $P < 0.001$) and weak correlation for T_{IMA} ($r = 0.386$, $P < 0.001$) against the criterion measure were also observed. T_{S} was also significantly correlated with T_{REC} ($r = 0.72$, $P \leq 0.0001$).

INSERT FIG.2 HERE.

Cross correlation analysis showed that T_{TEM} displayed a time lag when compared to T_{REC} . This was evident 45 min into the measurement protocol on visit 2 (30 min into exercise) with a cross correlation function (CCF) value of 0.734, which equated to a T_{REC} of 38.53 ± 0.31 . A CCF value of 0.733 demonstrated a lag was still present 40 min into exercise at a T_{REC} temperature of $38.87 \pm 0.27^{\circ}\text{C}$.

Bland Altman analysis revealed a mean bias of 0.04°C and limits of agreement (LoA) ranging from -0.63 to 0.73 for T_{REC} vs T_{PILL} (Fig. 3a). T_{REC} vs T_{TEM} displayed a mean bias of 0.39°C with LOA ranging from -0.89 to 1.67°C (Fig. 3b). The mean bias between T_{REC} vs T_{AUR} was 0.56°C and showed LOA ranging from -0.45 to 1.57°C (Fig. 3c). The mean bias for T_{REC} vs T_{IMA} was 0.81°C with LOA

ranging from -1.42 to 3.05°C (Fig. 3d). Bland Altman analysis reveals that only T_{PILL} demonstrates a mean bias within an acceptable range for use in exercise settings (Fig. 3a).

INSERT FIG. 3 HERE.

4. Discussion

Accurate T_{CORE} readings during exercise induced hyperthermia are very important in order to prevent serious heat related illness (Casa *et al.* 2007; Byrne & Lim, 2007). In addition, progression from current valid methods which are often considered invasive and impractical is warranted (Low *et al.*, 2007; Moran & Mendal, 2002).

The aim of this study was to examine the validity of novel and existing methods of T_{CORE} measurement (using T_{REC} as the reference standard) during rest and exercise induced hyperthermia. In the current study, moderate intensity exercise imposed considerable thermal strain on the subjects, with comparable peak T_{REC} ranges ($38.9 - 40.3^{\circ}\text{C}$) to others (Easton *et al.*, 2007). This study found that only T_{PILL} met the criterion for validity when compared to T_{REC} . Both T_{PILL} and T_{TEM} showed no significant difference to T_{REC} , however, Bland Altman analysis revealed only T_{PILL} displayed an acceptable mean bias (0.04°C). This corresponds with most findings (Casa *et al.*, 2007; Easton *et al.*, 2007; Ganio *et al.*, 2009) but disagrees with others (Savoie *et al.*, 2015). T_{AUR} and T_{IMA} showed significantly lower readings than T_{REC} , in addition, T_{IMA} demonstrated a poor validity (mean bias; 0.81°C) and a weak relationship with the reference standard.

T_{REC} measurement is inexpensive, not susceptible to ambient temperature changes and is deemed a practical and valid measure of T_{CORE} in steady state exercise conditions (Byrne & Lim, 2007, Ganio *et al.*, 2009; Sawka & Wenger, 1988). In addition, the National Athletic Trainers' Association (NATA) support using T_{REC} as a monitoring tool to avoid heat illnesses in hyperthermic athletes (Casa *et al.*, 2015). In the present study, a considerable amount of the total data points for T_{REC} were lost (26.7%) due to the thermometer becoming dislodged during running trials. This was also reported by

others (McKensie & Osgood, 2004). This highlights an enormous practical flaw with using this measurement method during exercise where considerable movement is unavoidable. T_{REC} may provide insight into the potential of heat related damage during hyperthermia (Gagnon *et al.*, 2010). However, due to the practical issues highlighted above, relying on T_{REC} to monitor T_{CORE} during exercise induced heat stress may pose great risk to the athlete.

T_{PILL} has been deemed a valid measure of T_{CORE} , both at rest (Darwent *et al.*, 2011) and during exercise (Easton *et al.*, 2007; Ganio *et al.*, 2009; Lee *et al.*, 2000). T_{PILL} showed no significant difference and displayed good agreement with T_{REC} , which is comparable to others (Bagley *et al.*, 2011; Casa *et al.* 2007; Easton *et al.*, 2007). In this study, the telemetric intestinal pill was ingested 8 hours before T_{CORE} measurements began. This is deemed sufficient time to avoid temperature interference from fluid intake (Byrne & Lim, 2007; Lee *et al.*, 2000). Nevertheless, during one trial four data points were discarded due to obvious cooling following fluid ingestion, this has also been reported by others (Easton *et al.*, 2007; Engels *et al.*, 2009; Savoie *et al.*, 2015; Wilkinson *et al.*, 2008). Lee *et al.* (2000) proposed an optimal sensor ingestion time of 6 hours prior to data collection to allow the device to pass the stomach and avoid potential temperature fluctuations while passing through the gastrointestinal tract. However, proposing a universal transit time is extremely difficult due to individual variability in gastrointestinal motility (Taylor *et al.* 2014). This aspect warrants further investigation.

No significant differences were observed between T_{TEM} and T_{REC} , however, mean bias was not acceptable (mean bias; 0.39°C). Despite attaining measurements from the temporal artery (which receives blood flow from the carotid artery) via infrared radiation, there is potential for this ‘surface’ measurement site to be influenced by the surrounding environment. In support, Ganio *et al.* (2009) found that mean bias for T_{TEM} improved when measurements were taken in a controlled indoor laboratory environment as opposed to outdoor measurements in the heat. Cross-correlation analysis performed in this study revealed that T_{TEM} displayed a lag when compared to T_{REC} , which was most prominent 30 min into exercise (T_{REC} ; $38.53 \pm 0.31^{\circ}\text{C}$). Greater heat storage can be assumed at the rectal site due to a lack of blood perfusion and proximity to the working musculature when compared

to the temporal measurement site (Taylor *et al.*, 2014). Currently, the algorithms employed in the temporal scanning device do not accurately consider the skin to core temperature gradient in hyperthermic individuals. Hence, despite the practical advantages of this method, this confirms that T_{TEM} does not show good agreement with other validated techniques (T_{REC} & T_{PILL}) within exercise science (Casa *et al.*, 2007; Kistemaker *et al.*, 2006).

Others state that direct measurement of the tympanic membrane is a valid measure of T_{CORE} (Benzinger & Benzinger, 1972) and is responsive to changes in central blood temperature (Jay *et al.*, 2007; Lim *et al.*, 2008). In the present study, when T_{AUR} was measured using a hand held commercial device, it registered significantly lower readings than T_{REC} throughout moderate intensity exercise. This is consistent with other findings (Easton *et al.*, 2007; Ganio *et al.*, 2009; Lim *et al.*, 2008). A possible cause for the lower T_{AUR} values is the influence of surrounding environmental conditions, evaporative cooling and variation in temperature gradients within the ear canal (Bagley *et al.*, 2011; Engels *et al.*, 2009; Lee *et al.*, 2000). This occurred despite efforts to achieve a measurement from as close to the tympanic membrane as possible. Significant differences were noted between T_{AUR} and T_{REC} when initial resting measurements were taken at comfortable thermal conditions ($23.2 \pm 1.5^{\circ}\text{C}$). No significant difference between T_{AUR} and T_{REC} existed following 15 min rest in the heated chamber ($29.8 \pm 0.9^{\circ}\text{C}$), which is consistent with previous findings (Easton *et al.*, 2007). This would support the influence of environment on this measurement device, despite an approximate average difference of 7°C between the two environmental conditions. Similar to the T_{TEM} site, changes in the subject's thermoregulatory response, for example increased peripheral vasodilation, may also be influential. Easton *et al.* (2007) suggested that the model of the thermometer may influence the T_{CORE} reading, with findings of good validity between T_{TYM} and T_{REC} at elevated T_{REC} temperatures (38.9°C). In this case, a Braun Thermoscan 4000 ExacTemp was used, which like other devices uses algorithms to estimate T_{CORE} (in this case, oral equivalent) via the infra-red radiation from the tympanic membrane. Currently it can be concluded that the algorithms used to estimate T_{CORE} are not robust enough to achieve accurate temperature measurements during exercise induced hyperthermia.

Anatomical depressions in the face (e.g. inner eye canthus) receive blood flow originating from the carotid artery. Due to considerable hyperaemia and sweating occurring at the head during intense exercise (particularly in warm conditions), peak temperature at the face may accurately reflect T_{CORE} . Ring *et al.* (2010) recorded comparable T_{CORE} readings to the current study (peak exercise values; $38.3 \pm 0.4^{\circ}\text{C}$) during facial imaging of fever in patients. To our knowledge, there is no published data to examine the agreement of T_{IMA} against T_{REC} as a reference standard during severe exercise induced hyperthermia (T_{REC} ; 39.6 ± 0.81). Our results correspond well with Teunissen and Daanen (2011), who found poor agreement between T_{IMA} (inner eye canthus) and oesophageal temperature during active and passive heating. All exercise readings for T_{IMA} were significantly lower than T_{REC} . As with other ‘surface’ measures T_{IMA} has greater susceptibility to environmental and peripheral physiological variability. Hence, despite the potential for technological advances in thermal imaging equipment, T_{IMA} is likely to provide different absolute measurement values to ‘deeper’ T_{CORE} measures. Currently this is not a valid method of T_{CORE} when compared to T_{REC} . In addition, the small number of trials in which T_{IMA} was used in this study are not enough to determine validity conclusively. More extensive research on the validity of this measure is recommended.

In conclusion, this study supports the use of T_{PILL} as a valid and practical measurement of T_{CORE} during rest and exercise induced hyperthermia when compared to T_{REC} . Due to potential confounding factors with both T_{REC} (thermometer dislodging) and T_{PILL} (fluid ingestion, loss of radio transmission and expulsion of the device), relying on one of these measures alone is not recommended. Devices which attain readings from the body’s ‘surface’ show poor agreement with T_{REC} , providing lower T_{CORE} readings during hyperthermia in steady state exercise conditions. This is also the case for T_{IMA} as a novel measure. Therefore, it is apparent that as a matter of some urgency, further research is required to robustly determine which T_{CORE} measure(s) is the most fit for purpose for monitoring the hyperthermic athlete.

Word Count: 4, 101 (incl. Abstract)

References

- Armstrong, L. E., Maresh, C. M., Crago, A. E., Adams, R., & Roberts, W. O. (1994). Interpretation of aural temperatures during exercise, hyperthermia and cooling therapy. *Medicine, Exercise, Nutrition & Health*, 3(1), 9 - 16.
- Bagley, J. R., Judelson, D. A., Spiering, B. A., Beam, W. C., Bartolini, J. A., Washburn, B. V. & Casa, D. J. (2011). Validity of field expedient devices to assess core temperature during exercise in the cold. *Aviation, Space, and Environmental Medicine*, 82(12), 1098-1103.
- Benzinger, M., & Benzinger, T. (Eds.). (1972). (Eds.). *fifth symposium on temperature* [Tympanic clinical temperature]. Washington D.C: American Institute of Physics, Instrument Society of America, pp. 2089 – 2102.: National Bureau of Standards.
- Bland, J. M., & Altman, D. G. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet (London, England)*, 1(8476), 307-310. doi:S0140-6736(86)90837-8 [pii]
- Borg, G. (1970). Perceived exertion as an indicator of somatic stress. *Scandinavian Journal of Rehabilitation Medicine*, 2(2), 92-98.
- Bourlai, T., Pryor, R. R., Suyama, J., Reis, S. E., & Hostler, D. (2012). Use of thermal imagery for estimation of core body temperature during precooling, exertion, and recovery in wildland firefighter protective clothing. *Prehospital Emergency Care : Official Journal of the National Association of EMS Physicians and the National Association of State EMS Directors*, 16(3), 390-399. doi:10.3109/10903127.2012.670689 [doi]
- Byrne, C. & Lim, C. L. (2007). The ingestible telemetric body core temperature sensor: A review of validity and exercise applications. *British Journal of Sports Medicine*, 41(3), 126-133. doi:bjsm.2006.026344 [pii]

- Casa, D. J., Becker, S. M., Ganio, M. S., Brown, C. M., Yeargin, S. W., Roti, M. W. & Maresh, C. M. (2007). Validity of devices that assess body temperature during outdoor exercise in the heat. *Journal of Athletic Training*, 42(3), 333-342.
- Casa, D. J., DeMartini, J. K., Bergeron, M. F., Csillan, D., Eichner, E. R., Lopez, R. M., Ferrara, M. S., Miller, K. C., O'Connor, F., Sawka, M. N. and Yeargin, S. W. (2015). National Athletic Trainers' Association Position Statement: Exertional Heat Illnesses. *Journal of Athletic Training*. 50(9), 986 – 1000.
- Childs, C., Vail, A., Protheroe, R., King, A. T., & Dark, P. M. (2005). Differences between brain and rectal temperatures during routine critical care of patients with severe traumatic brain injury. *Anaesthesia*, 60(8), 759-765. doi:ANA4193 [pii]
- Costello, J. T., Stewart, I. B., Selfe, J., Karki, A. I., & Donnelly, A. E. (2013). The use of thermal imaging in sports medicine research; a short report. *International Sports Medicine Journal*, 14(2), 94 - 98.
- Darwent, D., Zhou, X., van den Heuvel, C., Sargent, C., & Roach, G. D. (2011). The validity of temperature-sensitive ingestible capsules for measuring core body temperature in laboratory protocols. *Chronobiology International*, 28(8), 719-726. doi:10.3109/07420528.2011.597530 [doi]
- Davis H. A. (1983). Anaerobic threshold and lactate turn point. *European Journal of Applied Physiology*, 50, 383 —392.
- Deschamps, A., Levy, R. D., Cosio, M. G., Marliss, E. B., & Magder, S. (1992). Tympanic temperature should not be used to assess exercise induced hyperthermia. *Clinical Journal of Sports Medicine*, 2(1), 27 - 32.

- Durnin, J. V., & Womersley, J. (1974). Body fat assessed from total body density and its estimation from skinfold thickness: Measurements on 481 men and women aged from 16 to 72 years. *The British Journal of Nutrition*, 32(1), 77-97.
- Easton, C., Fudge, B., & Pitsiladis, Y. P. (2007). Rectal, telemetry pill and tympanic membrane thermometry during exercise heat stress. *Journal of Thermal Biology*, 32, 78 - 86.
- Engels, H. J., Yarandi, H. N., & Davis, J. E. (2009). Utility of an ingestible capsule for core temperature measurements during body warming. *Journal of Exercise Physiology (Online)*, 12(1), 1 - 9.
- Gagnon, D., Lemire, B. B., Jay, O. & Kenny, G. P. (2010). Aural canal, esophageal and rectal temperatures during exertional heat stress and the subsequent recovery period. *Journal of Athletic Training*, 45(2), 157 – 163.
- Ganio, M. S., Brown, C. M., Casa, D. J., Becker, S. M., Yeargin, S. W., McDermott, B. P. & Maresh, C. M. (2009). Validity and reliability of devices that assess body temperature during indoor exercise in the heat. *Journal of Athletic Training*, 44(2), 124-135. doi:10.4085/1062-6050-44.2.124 [doi]
- Gant, N., Atkinson, G., & Williams, C. (2006). The validity and reliability of intestinal temperature during intermittent running. *Medicine and Science in Sports and Exercise*, 38(11), 1926-1931. doi:10.1249/01.mss.0000233800.69776.ef [doi]
- Huggins, R., Glaviano, N., Negishi, N., Casa, D. J., & Hertel, J. (2012). Comparison of rectal and aural core body temperature thermometry in hyperthermic, exercising individuals: A meta-analysis. *Journal of Athletic Training*, 47(3), 329-338. doi:10.4085/1062-6050-47.3.09 [doi]
- James, C. A., Richardson, A. J., Watt, P. W., & Maxwell, N. S. (2014). Reliability and validity of skin temperature measurement by telemetry thermistors and a thermal camera during exercise in the heat. *Journal of Thermal Biology*, 45, 141 - 149.

- Jay, O., Reardon, F. D., Webb, P., Ducharme, M. B., Ramsay, T., Nettlefold, L., & Kenny, G. P. (2007). Estimating changes in mean body temperature for humans during exercise using core and skin temperatures is inaccurate even with a correction factor. *Journal of Applied Physiology* (Bethesda, Md.: 1985), 103(2), 443-451. doi:00117.2007 [pii]
- Kistemaker, J. A., Den Hartog, E. A., & Daanen, H. A. (2006). Reliability of an infrared forehead skin thermometer for core temperature measurements. *Journal of Medical Engineering & Technology*, 30(4), 252-261. doi:W81566L21355P888 [pii]
- Kolka, M. A., Quigley, M. D., Blanchard, L. A., Toyota, D. A., & Stephenson, L. A. (1993). Validation of a temperature telemetry system during moderate and strenuous exercise. *Journal of Thermal Biology*, 18(4), 203 - 210.
- Lee, S. M. C., Williams, W. J., & Schneider, S. M. (2000). Core temperature measurement during submaximal exercise: Esophageal, rectal and intestinal temperatures. *Aviation, Space and Environmental Medicine*, 17(9), 939 - 945.
- Lim, C. L., Byrne, C., & Lee, J. K. (2008). Human thermoregulation and measurement of body temperature in exercise and clinical settings. *Annals of the Academy of Medicine, Singapore*, 37(4), 347-353.
- Low, D. A., Vu, A., Brown, M., Davis, S. L., Keller, D. M., Levine, B. D., & Crandall, C. G. (2007). Temporal thermometry fails to track body core temperature during heat stress. *Medicine and Science in Sports and Exercise*, 39(7), 1029-1035. doi:10.1249/mss.0b013e318050ca3e [doi]
- McKenzie, J. E., & Osgood, D. W. (2004). Validation of a new telemetric core temperature monitor. *Journal of Thermal Biology*, 29(7 - 8), 605 - 611.
- Molnar, G. W., & Read, R. C. (1974). Studies during open-heart surgery on the special characteristics of rectal temperature. *Journal of Applied Physiology*, 36(3), 333-336.

- Moran, D. S., & Mendal, L. (2002). Core temperature measurement: Methods and current insights. *Sports Medicine (Auckland, N.Z.)*, 32(14), 879-885. doi:321401 [pii]
- O'Brien, C., Hoyt, R. W., Buller, M. J., Castellani, J. W., & Young, A. J. (1998). Telemetry pill measurement of core temperature in humans during active heating and cooling. *Medicine and Science in Sports and Exercise*, 30(3), 468-472.
- Ring, E. F., & Ammer, K. (2012). Infrared thermal imaging in medicine. *Physiological Measurements*, 33, R33 - R46.
- Ring, E. F., McEvoy, H., Jung, A., Zuber, J., & Machin, G. (2010). New standards for devices used for the measurement of human body temperature. *Journal of Medical Engineering & Technology*, 34(4), 249-253. doi:10.3109/03091901003663836 [doi]
- Robinson, J., Charlton, J., Seal, R., Spady, D., & Joffres, M. R. (1998). Oesophageal, rectal, axillary, tympanic and pulmonary artery temperatures during cardiac surgery. *Canadian Journal of Anaesthesia = Journal Canadien d'Anesthesie*, 45(4), 317-323. doi:10.1007/BF03012021 [doi]
- Savoie, F. A., Dion, T. D., Asselin, A., Gariépy, C., Boucher, P. M., Berrigan, F. & Goulet, E. D. B. (2015). Intestinal temperature does not reflect rectal temperature during prolonged, intense running with cold fluid ingestion. *Physiological Measurement*. 36(2), 259.
- Sawaka, M. N. & Wenger, C. B. (1998). Physiological responses to acute exercise heat stress. In: Pandolf, K. B., Sawka, M. N., Gonzalez, R. R., (eds). *Human Performance Physiology and Environmental Medicine at Terrestrial Extremes*. Indianapolis, IL: Benchmark Press. 97 – 151.
- Shiraki, K., Konda, N., & Sagawa, S. (1986). Esophageal and tympanic temperature responses to core blood temperature changes during hyperthermia. *Journal of Applied Physiology*. 61(1), 98-102.

- Svedahl, K., & MacIntosh, B. R. (2003). Anaerobic threshold: The concept and methods of measurement. *Canadian Journal of Applied Physiology = Revue Canadienne De Physiologie Appliquee*, 28(2), 299-323.
- Taylor, N. A., Tipton, M. J., & Kenny, G. P. (2014). Considerations for the measurement of core, skin and mean body temperatures. *Journal of Thermal Biology*, 46, 72-101.
doi:10.1016/j.jtherbio.2014.10.006 [doi]
- Teunissen, L. P. T. & Daanen, H. A. M. (2011). Infrared thermal imaging of the inner canthus of the eye as an estimator of body core temperature. *Journal of medical engineering and technology*. 35(3-4), 134 – 138.
- Toner, M. M., Drolet, L. L., & Pandolf, K. B. (1986). Perceptual and physiological responses during exercise in cool and cold water. *Perceptual and Motor Skills*, 62(1), 211-220.
doi:10.2466/pms.1986.62.1.211 [doi]
- Wilkinson, D. M., Carter, J. M., Richmond, V. L., Blacker, S. D., & Rayson, M. P. (2008). The effect of cool water ingestion on gastrointestinal pill temperature. *Medicine and Science in Sports and Exercise*, 40(3), 523-528. doi:10.1249/MSS.0b013e31815cc43e [doi]